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Characteristics of biomass in flameless combustion: A review

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ABSTRACT

The demands of energy and pollutant emissions reduction have motivated the combustion researchers to work on combustion improvement. Flameless combustion or high temperature air combustion has many features such as flame stability, low pollutant emission and uniform profiles of temperature compared to the other modes of combustion. Combustion of solid fuels likes biomass and wastes in flameless combustion conditions has not been investigated as comprehensive as combustion of gaseous fuels. The aim of using biomass in combustion is to reduce the pollutant emissions and to decrease the rate of fossil fuel consumption. In this review, combustion characteristics of biomass in flameless combustion are explained. The paper summarizes the research on the mass loss, ignition time, and NO_x emissions during biomass flameless combustion. These summaries show that biomass under flameless combustion gives low pollutant emissions, low mass loss and it decreases the ignition time.

Contents

1. Introduction

Energy supply is the basic request of humankind, for cooking, heating, manufacturing, electricity generation and transportation. Most of the energy demand of the world relies on the energy generation by combustion [1]. Improvement in the energy efficiency during the past few decades resulted in a reduction of the amount of energy required to generate a unit of gross domestic product (GDP) and hence, the rate of increase in global energy consumption has dropped significantly. Due to economic growth and population augmentation, the projection of global energy demands is about 80% of the world energy needs, and increases by 57% between the year 2004 and 2030. In 2030, fossil fuel combustion will fulfill about 80% of world energy needs. Fig. 1 illustrates the global energy consumption during the period 1980–2030 [2].

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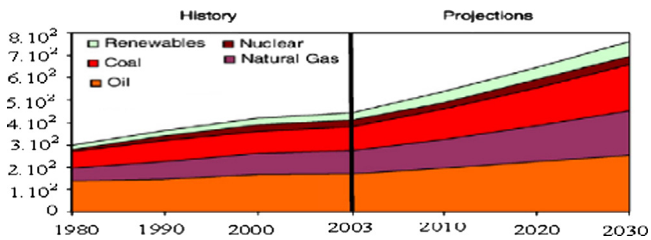

Fig. 1. Global energy consumption during the period 1980–2030 [2].

The term biomass stands for the waste from animal manure and/or for material derived from plants (i.e. wood, charcoal, or agriculture waste) and algae. The solar energy absorbed by plants, is used to the photosynthesis process which enables them to grow. This energy is called biomass energy, and it is stored in the plants and animals, or in the wastes. This energy could be recovered by using biomass as a fuel for combustion processes. Biomass energy could help to reduce the dependency on conventional fossil fuel products [3]. By some chemical, physical, and biological conversion processes, biomass could be transformed into liquid, gaseous, and solid forms, which can be easily burnt in combustion systems for power and thermal energy generation. Today, biomass contributes about 14% of the world total energy consumption, which is ranked as the fourth source of energy in the globe [4]. Biomass is the main source of energy for many developing countries. This is as high as 20% to 33%, but for the industrialized countries, biomass contributes about 9% to 14% of the total energy supplies. For some of the developing countries, biomass consumption reaches even over 50% to 90% of the total energy demand. In the poorer part of the inhabitants in developing countries, a large part of this biomass is used for cooking and heating and not for commercial purposes. Modern production of energy from biomass is applied for applications such as electricity generation, fuels for transportation and heat production for heavy industry in the industrialized countries. The energy demand from the biomass has strongly increased over the last decades in the developed countries such as the European Union [5]. The targeted ambitions of the European Union concerning the biomass usage are as high as 6000 PJ in the year 2010 (tripling the usage compared to the year 1999 levels), and possibly even more beyond the targets [6–8]. Today, pollutant emissions reduction from combustion process and saving energy are two common challenges for the researchers and industry [9,10]. The combustion researchers were exploring an alternative fuel and new regimes of combustion. Biomass is one of the alternative fuels in which its energy can be released in the combustion process. The term biomass stands for the waste from animal manure or for material derived from growing plants and all the organic materials derived from crops, trees, algae and plants [11]. The solar energy absorbed by plants, is used to the photosynthesis process which enables them to grow [12]. This energy is called biomass energy which is stored in the plants and animals, or in the wastes that they produce. This energy could be recovered by burning this biomass materials and use it as a fuel [13,64]. Biomass energy is considered to be one of the important parts of today's energy sources. This biomass energy could help the human to reduce their dependency on petroleum products, natural gas and coal. By some chemical, physical, and biological conversion processes the biomass could be transformed into liquid, gaseous, and solid fuels [14,15]. The transformation of biomass materials has a precise objective: to convert the carbonaceous solid material which is originally difficult to handle for bulky, and which is of low energy concentration, into the liquid fuels having physico-chemical characteristics that permit easy and economic storage and transferability through pumping systems [16]. The use of biomass products offers significant benefits as far as the environment issue is concerned. Biomass material absorbs carbon dioxide during growth and releases it during combustion. Therefore, biomass energy helps recycling the atmospheric carbon dioxide and does not contribute a net greenhouse effect. The biomass energy is mainly produced from wood and its wastes (64%), followed by municipal solid waste (24%), agricultural waste (5%), and landfill gases (5%) [13]. The process of producing biomass fuel is economically with negligible or even positive environmental effects through perennial crops. One of the oldest conversion methods to transform biomass into energy is the combustion due to its versatile character. In sequence to carry on to the latest conversion techniques, the combustion technology acquires constant improvements. The main advantages of this technology are already known in flameless combustion [17]. This technology has many names for examples high temperature air combustion (HTAC) [18], moderate or intense low oxygen dilution (MILD) combustion [19], Flameless Oxidation (FLOX) [20] and Colorless combustion [21]. In this paper, we referred to this technology by flameless combustion. The flameless combustion burner provides the following advantages; it reduces fuel consumption, reduces pollutant emission such as NO_x emission, stable and efficient combustion, enhanced heat transfer and low combustion noise [22–24]. Several studies have been conducted in the area of gaseous fuel combustion using flameless combustion facilities, but little attention was given on the behavior of solid biomass combustion in flameless condition. This paper will summarize the biomass behavior in the flameless combustion.

2. Biomass combustion

The process of the combustion is an overall exothermic set of reactions. The energy stored in the chemical bonds of a fuel is converted to heat energy and it can be used in different places such as heavy industry and a power plant to generate required steam for turbines that finally produce electricity and heat. In the case of the alternative fuel such as biomass, the combustion means burning of organic materials. In biomass combustion, wood is the most widely used fuel for burning. On the other hand, there is an increasing interest in other biomass types such as bark, tops and branches, straw, sawdust, waste wood or demolition wood, and energy crops (such as poplar and willow) [25–28]. The biomass combustion is a sequence of chemical reactions in which carbon is oxidized into carbon dioxide, and hydrogen is oxidized into the water. Incomplete combustion leads to formation of many unwanted products due to lack of oxygen [29]. The combustion air requirement depends on the physical and chemical characteristics of the fuel and the excess air is used to cool the systems. The excess air ratio is one of the main combustion parameters for high combustion efficiency. In most applications, the excess air ratio is far higher than the stoichiometric amount and the locally available combustion air. Biomass combustion depends on the following factors: the mass flow rate of fuel, the mass flow rate of combustion air for the complete combustion, the combustion products and the flame temperature. Due to high temperature, most reactions of the combustion are vapor phase reactions. During the normal combustion process, the flame burns efficiently when the oxygen is just enough to burn the existing fuel. Combustion could be maintained only if enough heat is present to raise the temperatures of unburned gases to necessary levels [30]. Generally, biomass combustion properties can be classified as microscopic and macroscopic. The microscopic examinations include thermal, chemical, kinetics, and mineral data. However, the macroscopic properties of biomass fuels are heating value, ultimate analysis,

moisture content, particle size, bulk density, and ash fusion temperature [31]. In combustion analysis, the biomass fuel properties can be grouped into physical, chemical, thermal and mineral properties. The physical properties such as density, porosity, and internal surface area are related to biomass species; whereas properties such as bulk density, particle size, and shape distribution are related to fuel preparation methods. Properties such as the proximate analysis, ultimate analysis, heating value of the volatiles, high heating value, analysis of pyrolysis products and heating value of the char are important chemical properties during combustion of the biomass fuel. On the other hand, properties such as thermal conductivity, emissivity that varies with moisture content, specific heat, temperature, and degree of thermal degradation by one order of magnitude are important thermal properties in the biomass combustion. The thermal degradation products during the biomass combustion consist of volatiles, moisture, char and ash. The volatile products are subdivided into gases such as carbon dioxide, carbon monoxide, light hydrocarbons, moisture, hydrogen and tars. These products depend on the temperature and heating rate of pyrolysis. Few properties are differed by location of the biomass, species, and growth conditions. Fig. 2 shows the biomass combustion diagram and carbon cycle closed loop. Additional properties depend on the environment of combustion [32].

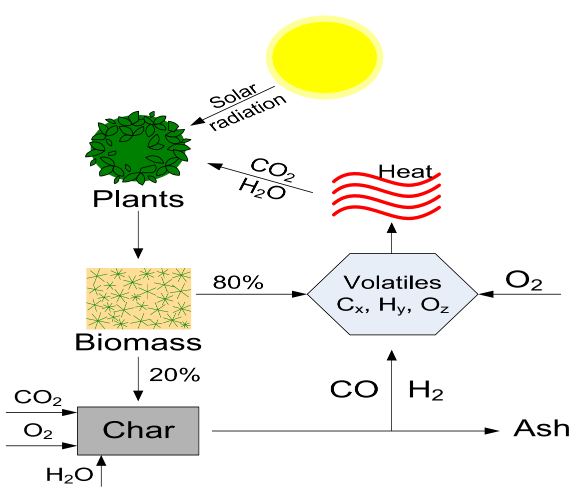

Fig. 2. Biomass combustion diagram and carbon cycle closed loop.

3. Concepts of biomass flameless combustion

Flameless combustion phenomenon has enormous effects on emission reduction and combustion performance improvement [33]. During an experiment in 1989, it was observed that when the furnace temperature was around 1000 °C and the preheated combustion air was about 650 °C the fuel was completely consumed without a visible flame as it has been shown in Fig. 3a. The results confirmed that combustion was stable, NO_x emissions was approximately zero, low noise and smooth with low carbon monoxide content in the exhaust (< 1 ppm)was reported [34]. Fig. 3b depicts conventional flame and flameless combustion modes.

One of the most important factors of the combustion efficiency and energy conversion is the flame temperature. The initial concept of excess enthalpy combustion was provided by Weinberg et al. [35]. They discussed the limitations of the flame combustion temperature, including both positive and negatives factors associated with combustion temperature in certain range. In this technology, the heat recirculation is the main factor. Heat circulation regime, using high-efficiency heat exchanger, was adopted in order to increase the combustion temperature and the associated energy savings. However, the scientists and combustion engineers need to reduce the flame temperature because of pollutant formation and material constraints used in the equipment. From this point, it is better to use the thermal energy generated by the combustion process, heat up the fuel or the combustion air, whatever is often of low thermal energy, than via the use of electrical or mechanical energy. The amount of generated energy circulated into the combustion process is given as

$$C_p dT_o = Q_c + Q_a = H_F - H_O \tag{1}$$

Where, T_F is the final temperature, T_o is the initial temperature, Q_c is the heat release by chemical energy conversion, Q_a is the energy added, H_F and H_o are the Enthalpy at the two states. The preheating enthalpy absorbed from the fuel gas and the fuel chemical enthalpy together are equal to the total enthalpy of the combustion system. In flameless mode, the enthalpy of the reaction zone is more than conventional combustion because the circled part of thermal energy from combustion products increases the combustion temperature. It results due to the use of a term called "Excess Enthalpy Combustion" [36–40]. Biomass flameless combustion mode is different from biomass conventional combustion. Flameless combustion could be characterized by external or internal recirculation and a very intensive mixing inside the combustion chamber. Thus, this technology occurs in a very large

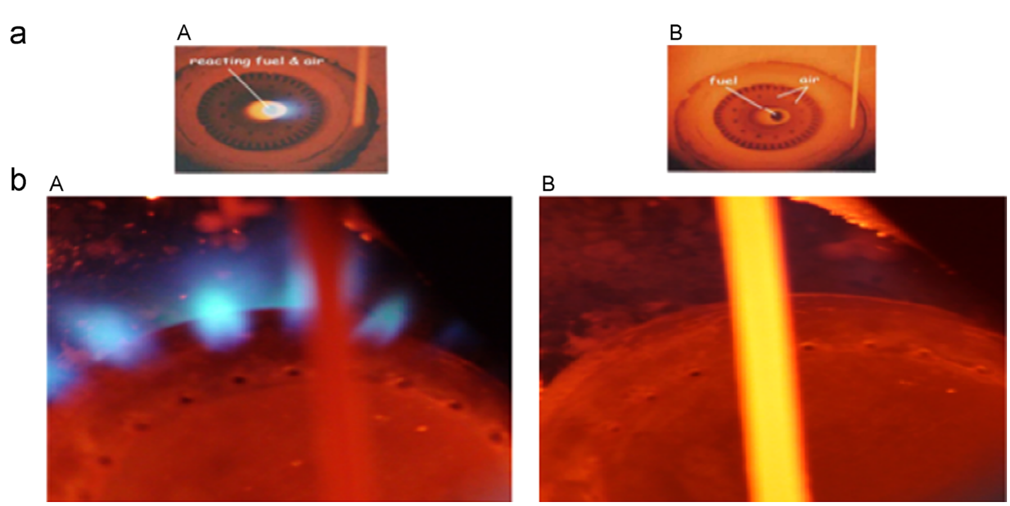

Fig. 3. (a) The flame mode in combustion A: conventional flame B: flamelss [63]. (b) Direct photographs of (A) visible flame (B) flameless combustion modes in HiREF experimental furnace.

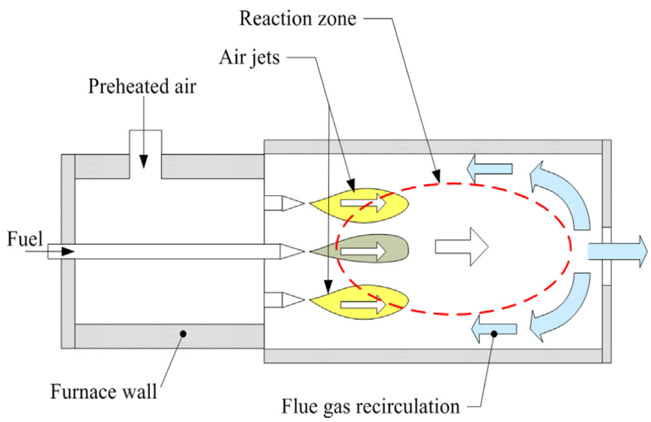

Fig. 4. A Typical flameless furnace [42].

volume with a relatively uniform distribution of the reacting species, temperature and heat fluxes. In the flameless combustion, biomass burns under high temperature of oxidizer and low oxygen concentration in the reaction zone. In flameless combustion technique, due to oxygen concentration reduction in the reaction zone, combustion spreads over a large volume, peak temperature decreases, heat flux and thermal efficiency increase and stable combustion is observed. When the conditions inside the chamber are stable and the mode of the flameless starts, the biomass sample is inserted into the reaction zone and kept for a specified duration of time. During the reaction, the temperature of the combustion air is above the auto ignition of the biomass [41,65]. To understand the flameless combustion properties of biomass in combustion chamber, the flame phenomenon and ignition time of wood pellets are discussed in this paper. In addition, NO_x emission during flameless combustion is explained. The principles of the flameless combustion for biomass have been studied by several researchers [42]. In these studies, biomass and air combustion were mixed with large amounts of recirculated exhaust gas, by that mean the reaction zone was diluted. Therefore, the flame temperature of the mixture decreased and the temperature of the reaction zone increased. Fig. 4 demonstrates the basic principle of the flameless combustion burner.

From this figure, it can be seen that the flue gas recirculating is mainly internal recirculation in which the air and fuel injected to the burner at non-premixed mode. In addition, it can be remarked that the reaction zone happens at downstream from the point of injection. For this reason low peak flame temperature and low oxygen concentration occurs in this area. That leads the combustion system to a low thermal NO formation, then low NO_x emissions and invisibly flame [43–46].

4. Design and configuration of biomass flameless combustion systems

It is a fact that the major challenge in the biomass flameless combustion research is about the design of burner and furnace. Such design determines the effectiveness of the combustion process in the flameless mode, and hence controls the ignition time, temperature uniformity and pollutant emissions. Therefore, it is vital to review and discuss the various designs and methods to achieve flameless combustion for different biomass fuels. The principle of the flameless combustion for biomass was investigated by Hykiri et al. [14]. In such study, biomass and air combustion were mixed with large amounts of recirculated exhaust gas to dilute the reaction zone. Due to that, the flame (i.e. peak) temperature decreased and the average temperature of the reaction zone increased. Fig. 4 shows the basic principle of the flameless combustion burner in such study. From this figure, it can be seen that the fuel gas recirculation was mainly internal recirculation and the air and fuel were injected to the burner at non-premixed configuration. In addition, it can be noted that the reaction zone is located downstream relatively far from the point of injection. For this reason, low peak temperature of the flame and low oxygen concentration can be found in this area [42,43].

5. Current researches on biomass under flameless combustion

Only few studies are conducted on the use of solid fuels, including biomass under flameless combustion conditions. The combustion characteristics and emissions under high temperature air combustion in a cylindrical furnace powered by pulverized bituminous and anthracite coal as a fuel were investigate by Suda et al. [44]. It was found that ignition delay decreases and volatiles release enhances. Also it was observed that NO_x emission reduces by 40% when the preheated air temperature increases during the experiment. A new design of burner for boiler applications, named Primary Air Enrichment and Preheating (PRP) burner was introduced by Zhang et al. [47] and Dally et al. [48] to fulfill the process of preheating. The PRP burner has a preheating chamber having one end connected to the primary air and the other end opened to the furnace. They found that when anthracite coal was used as fuel, a stable flame is obtained and reduction of 50% in NO_x emissions is achieved when compared to low NO_x burners. In addition, in the flameless combustion in which coal is applied as a fuel, a pre-combustor is added before the furnaces to supply high air preheat. The hot gas recirculation stream is developed through a reverse flow caused by the high momentum of the inlet fuel stream. Around 60–70% NO_x formation mitigation is possible by the application of low NO_x burner technology with fuel or air staging [49]. From the above, it can be construed that flameless combustion has the possibility to be utilized for solid fuels but unluckily very little records are available on how it can be best implemented.

6. NO_x emission

During the combustion of the biomass, three different formations of the nitric oxides are formed as follows:

1. Thermal NO_x: The construction of the thermal NO was corresponded to the direct oxidation of nitrogen molecules and the reaction takes place at high temperature.
2. Prompt NO_x (Fenimore): Prompt NO formation occurs in fuel-rich systems. It can be found in the flame zone involving a hydrocarbon species and atmospheric nitrogen.
3. Fuel NO_x: The fuel NO_x commonly arises from nitrogen-bearing fuels such as certain, solid and liquid. It is formed by the oxidation of the nitrogen contained in the fuel.

The formation of NO_x emission during flameless combustion using wood pellets as fuel was studied by Roman et al. [50]. The results show that the level of NO_x emission is proportional to the oxygen concentration in the combustion air and combustion air temperature. At very high combustion air temperature (1000 °C) the level of NO_x increases rapidly with oxygen concentration in combustion air. Figs. 5 and 6 show the variations of NO_x emission with time (s) at combustion air temperature 1000 °C and 800 °C respectively for different concentrations of oxygen in [50,66].

At the oxygen concentration of 70% the maximum level of NO_x emission was reported. At this point, the maximum level

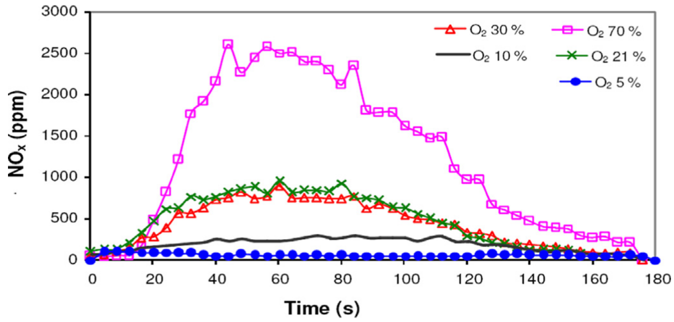

Fig. 5. Variation of NO_x emissions with time at different O_2 concentrations at 1000 °C [50].

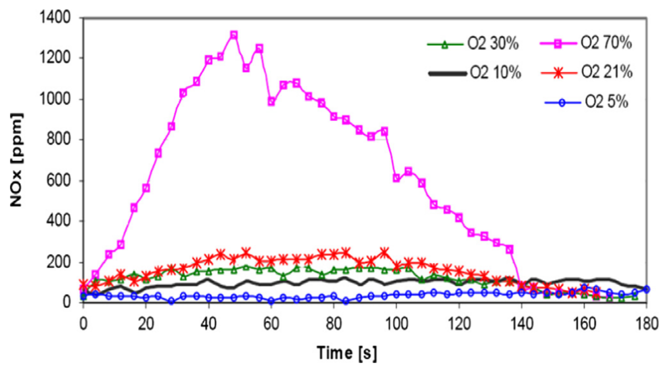

Fig. 6. Variation of NO_x emissions with time at different O_2 concentrations at 800 °C [50].

of NO_x emission resulted from two types of combinations; the first combination is between the nitrogen surrounded within the fuel matrix and the oxygen in excess; the second combination is between oxygen and nitrogen from air. The effect of high preheats air combustion on NO_x emission was studied by Choi and Katsuki [51]. Low NO_x emissions are achieved even under high temperature. This is one advantage of the flameless combustion. In addition it was stipulated that at diluted circumstances, the combustion can achieve NO_x emissions of 50 ppm [52]. This is in contrast to the case of traditional combustion technologies, which suffer from thermal NO_x when the combustion temperature increases [53,54]. In addition, in combustion of the biomass when the recirculation ratio of the flue gas increases, NO_x emission decreases after initial increase in the beginning, as in Fig. 7 [42].

The level of CO_2 and CO effects on the temperature and oxygen concentration of exhaust combustion gases. When the temperature increases from 800 °C to 1000 °C at 5% oxygen dilution CO emissions increase from 10.1% to 11.0%. From this result, it can be shown that the CO emissions are significant in the diluted condition of 5% oxygen concentration. For the CO_2 formation, it was noticeable for lower temperature and higher oxygen concentrations [50].

7. Mass loss

The mass loss phenomenon was divided into three stages by Kuo et al. [55,56]. First, the period before the ignition (from 100% to about 90% mass loss) corresponding to the drying stage. In this stage, the moisture and some gases from the decomposed biomass fuel are lost. Second, the flaming stage of combustion (between 90% to about 20%) corresponding to the volatiles combustion stage. In this stage, the volatile substances are released and burnt.

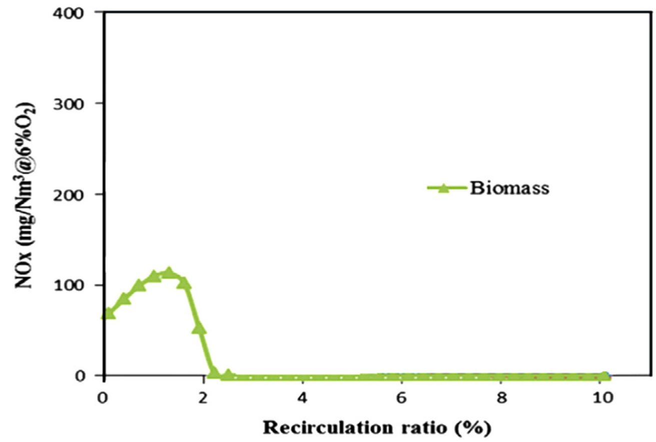

Fig. 7. The effect of the recirculation ratio on NO_x emissions for biomass [42].

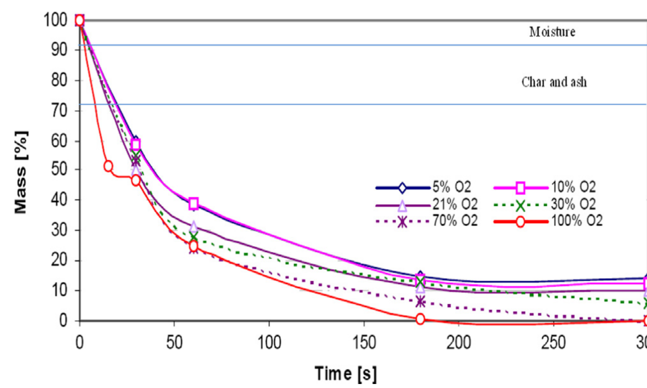

Fig. 8. Mass loss curves for different O_2 concentrations at 1000 °C [50].

Finally, at char stage of combustion (between 20% and 0% mass losses), char is consumed during the third mass loss stage [57,58]. During the combustion of biomass, the reduction of pellet mass depends on the oxidant temperature. The rate of mass loss increases when temperature increases. The rate of the mass loss in combustion of biomass depends on temperature during the drying and devolatilization phases. As the temperature increases, the heat transfer increases, which enhances the decomposition of the wood pellet. The mass loss rate at 1000 °C is observed to be higher than that at 1100 K [59]. In addition, as temperature increases from 800 °C to 1000 °C, the mass losses after 50 s for 5% and 10% oxygen concentrations increase by 33% and 39% respectively. From the presented result, the effect of temperature on mass loss is more pronounced in enriched oxygen concentrations. Fig. 8 demonstrates the effects of temperature on mass loss. Also, Fig. 9 illustrates that at 600 °C the mass loss rate does not depend on the oxygen concentration.

It has been reported that at low temperatures (below 250 °C) and for different oxygen concentrations, the mass loss rate of biomass combustion (wood) is similar [60]. That means the oxidant temperature plays important role in the rate of mass loss during biomass combustion which can be one of the advantages of flameless combustion. From Fig. 10, it can be found that there is no influence of oxygen concentration on mass loss at 600 °C. It was shown in the experimental works that different oxygen concentrations at very high oxidizer temperatures do not have a major influence on mass loss compared to the lower temperatures. Fig. 10 depicts the comparison of mass loss for different temperatures and O_2 concentration operations [61].

At temperatures between 180 and 230 °C a sudden of mass loss of the samples was started, which represents some volatiles and their ignition. The rate of mass loss proceeded so rapidly that it reaches its maximum value at the rapid burning region. At temperature between 330 and 430 °C, the rapid loss of mass is reported. After this temperature zone, the burning rate decreases, and consequently some small losses in the mass of the sample continued as long as the temperature increased up to 1000 °C, indicating slow burning of the partly carbonized residue [3]. This condition is referred to the biomass flameless combustion mode.

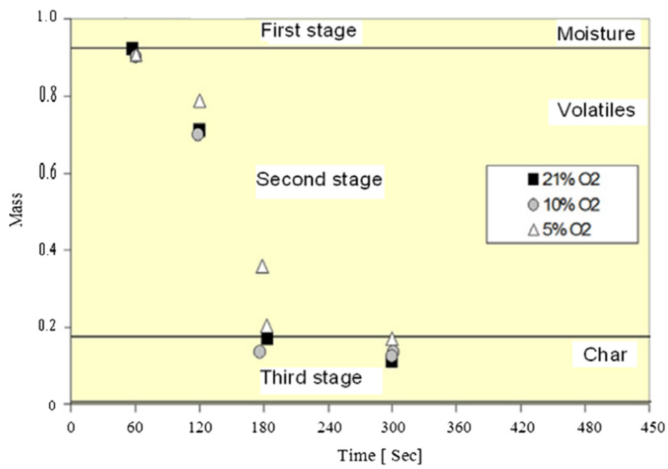

Fig. 9. Influence of the oxygen concentration on the wood pellet combustion for $T_{oxidizer}=600$ °C mass as function of time for different oxygen concentrations in the oxidizer [41].

8. Ignition time

The ignition delay or ignition time is extremely dependent on the combustion parameters such as oxygen concentration and oxidant temperature. In biomass combustion, the ash and moisture contents in the fuel cause ignition and combustion problems [62]. During solid fossil fuel utilization in the flameless combustion, a rapid heating of the combustible mixture in the combustion chamber facilitates pyrolysis to takes place. In addition, suppressing ignition delay, volatile matter releases processes for the fuel particles and combustion stability were reported [47]. The ignition delay almost depends on the oxygen concentration at high temperature of oxidant (1000 °C) and highly dependent on the oxygen concentration at low temperatures (600 °C). At low oxygen concentrations (5%) of the oxidizer and low temperature 600 °C, the wood pellets did not ignite within 5 min. In the larger combustion volume, the ignition time was almost independent of the oxygen concentration when the oxidizer is preheated to 1000 °C. Also, it

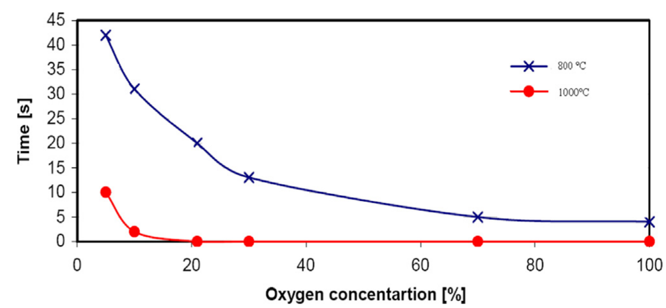

Fig. 11. Ignition delay for different O_2 concentrations and oxidant temperature [50].

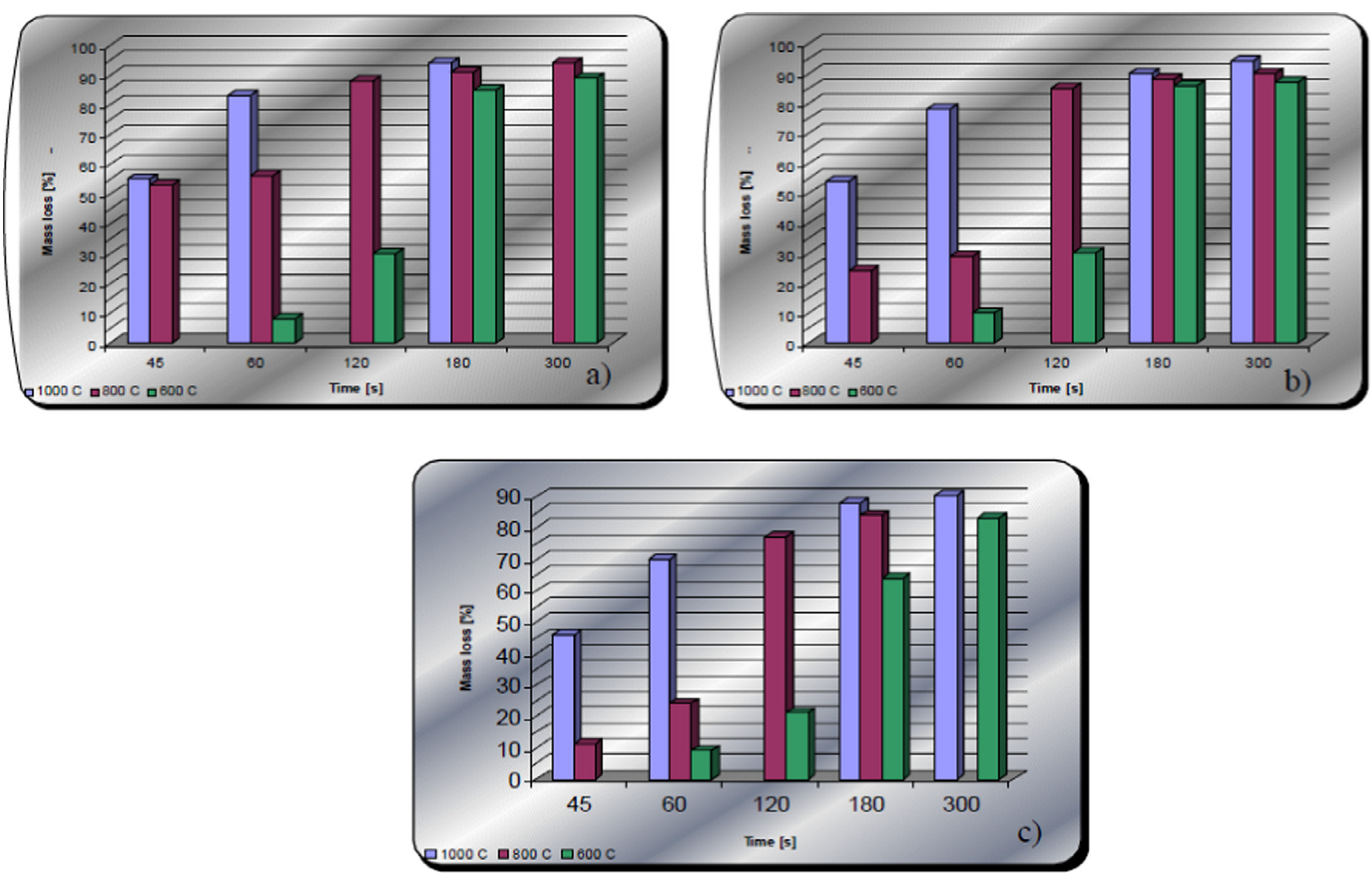

Fig. 10. The comparison of mass loss for different temperature and O_2 concentration [61].

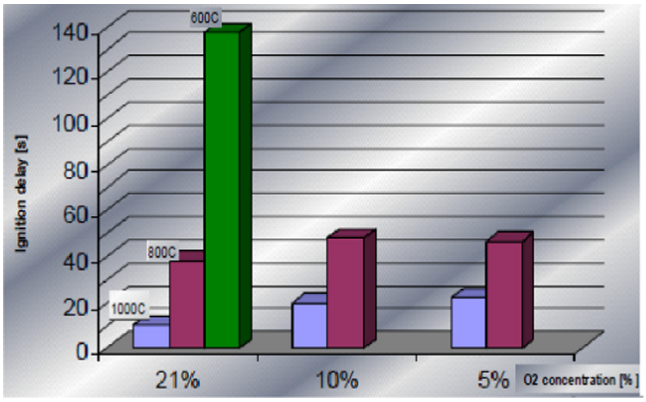

Fig. 12. Ignition delay for different temperatures and oxygen concentration wood pellets [49].

was reported that when oxidizer preheated up to 1000 °C and the oxygen concentration enhances up to 21%, delay time to flaming ignition does not occur. When oxygen concentration increases at a low oxidant temperature (800 °C) the delay time decreases. The effects of low and high temperatures and oxygen concentration on ignition time are shown in Fig. 11 [50].

The effects of higher temperature and oxygen enriched were invested and the results show that at 1000 °C, ignition occurs instantaneously for oxygen concentrations of 21% and above. At highly preheated air combustion when coal powder was used as a fuel it was observed that the ignition time decreases as the combustion air temperature increases from 350 °C to 800 °C, which was the same result when biomass was used as a fuel [44]. It was reported that during experimental work, the ignition delay increases with decreasing concentration of oxygen and decreasing oxidizer temperature. The delay connected with decreasing O_2 is longer for lower temperatures of oxidizer than for higher ones which are illustrated in Fig. 12 [61].

9. Conclusion

This review paper presented the combustion characteristics of biomass fuel in flameless combustion. The characters of biomass in flameless combustion were summarized in NO_x formation reduction, mass loss and ignition delay. Reviewed investigations confirm that the most effectiveness of biomass combustion under flameless combustion mode is NO_x emission reduction. In addition, the mass loss during the combustion of solid fuel decreases when the biomass applied as a fuel under flameless combustion. The ignition delay decreases due to high preheated air combustion and low oxygen concentration.

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